Capacitive voltage sensors – small cost, big convenience

Application Note

Your partner just bought one of those pen-shaped ac voltage detectors. He calls it a "tick-tracer" or a "glow-tip." You've seen him carry it in his shirt pocket wherever he goes. He must like it because he won't loan it out. When you asked him about it, he claimed that it can detect live voltage inside an insulated wire. He also says that it can quickly detect an open neutral in a branch circuit and in some cases it can spot a bad ground connection for a metal enclosure.

How does this thing work anyway? How can it detect voltage without making a metallic contact? Will it detect live conductors inside a grounded metal conduit?

The pen-shaped ac voltage sensors work on the principle of capacitive coupling. To understand this, let's return momentarily to electrical circuit theory and recall how a capacitor works. A capacitor has two conductors or "plates" that are separated by a non-conductor called a dielectric. If we connect an ac voltage across the two conductors, an ac current will flow as the electrons are alternately attracted or repelled by the voltage on the opposite plate. There's a complete ac circuit even though there's no "hard-wired" circuit connection. The electrical "field" inside the capacitor, between the two plates, is what completes the ac circuit.

We often think of capacitors as individual circuit components such as motor starting caps, but in reality, the world is full of small "stray" capacitors that we don't normally realize are present. Here's an example. Suppose you are standing on a carpeted concrete floor directly under a 120 V light fixture and the light is on. Your body is conducting a very small ac current because it is part of a circuit consisting of two capacitors in series. The two conductors or plates for the first capacitor are the live element in the light bulb and your body. The dielectric is the air (and maybe your hat) between them. The two conductors for the second capacitor are your body and the concrete floor (remember that concrete is a good conductor, which is why electrodes encased in concrete are used as earth grounds). The dielectric for the second capacitor is the carpet plus your shoes and socks. This second capacitor is much larger than the first. A very small ac current will flow because there is 120 V across the series combination. This current is significantly lower than the shock threshold or we wouldn't be living in a world of ac power and we definitely would not be turning on lights in the bathroom.

But how does the voltage divide between the two caps in series? This answer is critical to understanding how the capacitive voltage sensor works. Let's briefly return to our electrical circuit theory again. In a series circuit, the largest voltage will develop across the largest impedance (Ohm's Law). With capacitors, the smaller the capacitor, the larger the impedance (known as capacitive reactance). It's a little tricky, because it's the opposite of how resistors behave, but keeping this twist in mind, the rest is straightforward. When two capacitors are in series, the largest voltage will develop across the smallest capacitor. In the above example, only a few volts will develop between your feet and the floor (the large

capacitor) while the remainder of the 120 V will be between your head and the light bulb (the small capacitor). This may sound bizarre because we normally don't think of the carpet and floor as parts of an electric circuit but in fact they are and they will obey Ohm's Law and Kirchoff's Rules if we apply them correctly.

The capacitive voltage sensor works because when you hold the barrel in your hand and place the tip near a live conductor, you are inserting the high impedance sensing element into a capacitively coupled series circuit. As in the previous example, your hand and body form a relatively large capacitor coupled to the floor. The sensor tip is a small capacitor coupled to the live voltage. The sensing circuit detects the voltage and turns on a light or sounds the buzzer.

To test the theory try this simple test: Find a metal desk lamp that has a two-prong power cord, such as a lamp that is not grounded. Plug the cord into a live outlet and with the sensor in your hand, touch the tip to the metal frame of the lamp. The sensor should indicate live voltage because the metal frame of the lamp is near (capacitively coupled to) the hot side of the line cord and there is no grounding conductor to "draw down" the voltage. In other words, the sensor detects the "stray" voltage coupled to the light frame by the "stray" capacitance between the frame and the hot side of the line. Now, rest the sensor on a stack of books or other non-conductive object so that the tip remains in contact with the lamp frame while you take your hand away. The sensor will no longer indicate live voltage because its capacitively coupled circuit was broken when you took your hand away!

This test demonstrates how the sensor can detect an open neutral in a branch circuit. Let's assume the circuit you are testing is a 120 V wall outlet. When you plug in a load, nothing happens. A quick check of the panel shows that the correct circuit breaker is on and your multimeter measures 120 V between the hot and ground at the outlet. Next, you take out your sensor and insert the tip into the hot side of the outlet – it indicates live voltage. Then, you insert the tip into the neutral side of the outlet with the same results – a live voltage indication. How can this be? If the neutral were in contact with the hot conductor, wouldn't we have a short circuit? Wouldn't the breaker be tripped? If we think carefully about capacitive coupling, the answer is obvious. The hot and neutral conductors are lying side by side for the complete distance from the outlet back to the panel. In other words, they are capacitively coupled together: each wire is one "plate" of the capacitor and the conductor insulation is the dielectric. If the neutral is open at the panel, and therefore not grounded, the neutral conductor will float up to nearly the same voltage as the hot. That's why the voltage sensor indicates live voltage on the neutral.

Try this yourself with a pair of two-prong extension cords. Plug one cord into a wall outlet and plug the second cord into the first but connect only the hot side leaving the neutral open. Go to the loose end of the second cord and try the voltage sensor in both sides. They both should indicate live voltage.

Under certain conditions we can use the voltage sensor to detect a bad ground connection on a metal enclosure or section of conduit. In fact, this is a good habit to get into before contacting or working on any electrical enclosure. Think of the lamp frame test described earlier. The reason the sensor indicated live voltage on the frame was because the ungrounded metal frame had stray voltage on it coupled from the hot conductor. In the case of the ungrounded metal enclosure, the voltage sensor won't tell you if the enclosure is just "hot" from capacitively coupled voltage, or if it's really hot from contact with a live wire (frayed insulation on a phase conductor). The difference can be life or death. It's worth checking out.

Testing with a capacitive voltage sensor has certain limitations which you need to remember. Correct operation of the tester depends upon the capacitance between the sensor's barrel and ground (normally through your hand and body). If this path is broken for any reason, the sensor probably won't work. For example, if you are standing on a wooden ladder, the capacitance between your body and ground will be much less than if you were standing on a concrete floor. Remember, in a series circuit, the smaller the capacitance, the greater the voltage drop. There might be too much voltage drop from you to the floor and too little across the sensor. The sensors will have a certain minimum voltage to turn on (90 V in the case of the 120 V version of the Fluke VoltAlert.™ In our wooden ladder scenario, the sensor might not turn on despite the circuit being hot. By similar reasoning, the sensor cannot detect live conductors inside a grounded metal conduit.

Good safety practice dictates that you verify the sensor's operation on a known live circuit both before and after you test an unknown circuit. The same practice applies to multimeters. If there is any doubt in your mind about whether the circuit is truly live or dead, use an additional method to verify the test results. You only have to be right once to make it all worthwhile.

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